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THE POTENTIAL FOR ASTROMETRY IN THE INFRARED*

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ABSTRACT

Infrared interferometry promises to be a useful astrometric technique. Preliminary measurements of the star α Orionis made with a heterodyne interferometer exhibit phase coherence over a period of at least 1000 seconds. The measurements were equivalent to a positional determination of 60 milliarcsecond accuracy every 5 seconds of integration.

1. INTRODUCTION

In the optical region, atmospheric seeing usually amounts to 1 arcsecond or more. This means that for apertures larger than about 10 cm the optical resolution obtainable with a single telescope is dominated by atmospheric effects and is hence independent of telescope size. In order to estimate the likely effect of seeing in the infrared we turn to the theory of Kolmogorov and Obukhov. For turbulent eddies within the inertial subrange, that is, for turbulence of characteristic size larger than that which will be damped out but smaller than the dimension of the macroscopic flow pattern, the theory predicts that angular resolution will increase as $\lambda^{1/5}$. Thus at 10 microns, one expects the seeing disc to be smaller than it is in the visible by a factor of 1.82. (A more complete discussion is available in Tatarski[1] and in Fried[2])

In view of the importance of this result to infrared astrometry it is unfortunate that few extensive experimental results on the subject have been reported. Boyd[3] has made one such study at the McMath solar telescope using a 10 micron imaging upconverter. Using the 60" telescope, he measured the effect of seeing on the solar limb at 10 microns and in the visible under a

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variety of seeing conditions. He found good agreement with theoretical expectations, obtaining a value of 1.9 ± 0.2 for the improvement in seeing in the infrared.

Betz[4], using a heterodyne receiver, has compared signal intensities from the star α Orionis as received on the 30" and 60" McMath telescopes. With a heterodyne detector only one spatial mode is received, and hence on a point source the detected signal is a measure of the degree of coherence of the wavefront reaching the telescope. Under good conditions, Betz found a signal increase in proportion to telescope area, implying no loss of coherence in going from 30" to 60" mirrors. It is thus apparent that quite large telescopes will give a coherent infrared image under good conditions.

The theoretical improvements in seeing mentioned above assume that the refractive index fluctuations at 10 microns have the same magnitude as in the visible. While this will be true for temperature induced fluctuations, the effect of perturbations in water vapour content is minimized at 10 microns due to the indices of refraction of water vapour and air of the same density being identical at this wavelength[5]. Thus it seems likely that, in addition to the $\lambda^{1/5}$ improvement in resolution discussed above, infrared astrometry will be less sensitive to large scale meteorological phenomena involving gradients in water vapour content.

2. HETERODYNE INTERFEROMETER RESULTS

Some preliminary measurements relevant to astrometry have been made by the Berkeley group using a 10 micron heterodyne interferometer. The interferometer operates at the McMath solar telescope at KPNO on Kitt Peak in Arizona. The two 30" auxiliary telescopes are used, giving us a fixed east-west baseline of 5.5 meters. An infrared interferometer of this type is directly analogous to a radio interferometer, and after the mixer stages the intermediate frequency signals are processed in essentially the same manner. Referring now to Figure 1, infrared radiation from the telescope is focussed onto the detector, a HgCdTe photodiode operating at liquid nitrogen temperature. Also incident on the detector is a milliwatt of local oscillator carrier, generated by a CO_2 laser operating at 11.1 microns. The resulting

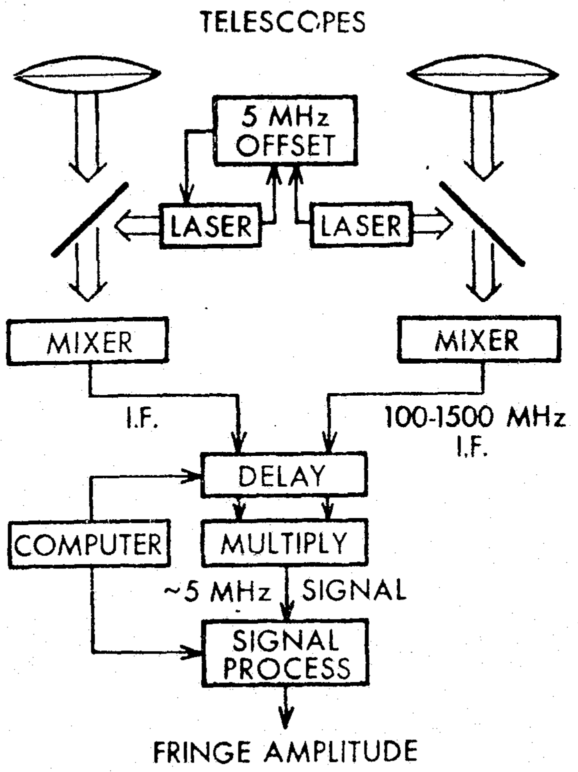

Figure 1: Heterodyne Interferometer

photocurrent consists of a dc component produced by rectification of the laser power, plus sum and difference frequencies generated by beating between the laser carrier and the infrared signal from the star, plus some higher order terms which are essentially negligible. It is the mixing products we are interested in, and by amplifying the diode output in a wideband transistor amplifier, an infrared band extending 1400 MHz above and below the laser frequency can be detected.

In order that the phase relationships between the two i-f signals be preserved the laser local oscillators must bear a known phase relationship to each other. This is achieved by directly beating the laser outputs together in a third HgCdTe photodiode and using the resulting beat note to phase-lock one laser to the other. For convenience the two lasers are offset by 5 MHz. This offset appears in the i-f signals but is later removed in the signal processing.

After amplification the i-f signals are passed through a switched delay line and multiplied together to correlate the phase information in each. In order that no information be lost, the total signal paths must be equalized to within a small fraction of the coherence length, $c/\Delta\nu$. For a bandwidth $\Delta\nu$ of 3 GHz the coherence length is 10 cm. The differential path length is constantly changing as the star moves across the sky, and hence a computer is used to switch additional 4.8 cm lengths of coaxial line into the west side at intervals throughout the integration. Because of the double sideband nature of the detection process, the phase of the interference signal undergoes only a very small discontinuity when the delay line switches. The discontinuity arises only because of the 5 MHz offset between the i-f signals and amounts to 3×10^{-3} radians. It should be noted, however, that with single-sideband detection - for example if one were to contemplate interferometry of narrow infrared fine-structure or molecular lines - one would need to monitor the delay line steps with high precision to avoid destroying phase information.

After correlation, the 5 MHz fringe signal is heterodyned again to remove the laser offset frequency. For the present 5.5 meter baseline, the resulting fringe signal lies at a frequency between 0 and 40 Hz as the star moves through the fringe pattern of the telescopes. Analysis of the interference signal begins by performing a Fourier transform. Figure 2 shows a fringe obtained on the star α Orionis last September, under conditions of very good seeing[6]. The power spectrum is unresolved at 0.001 Hz resolution, implying phase coherence over the full 1000 second integration. If we determine the fringe phase at each 5 second interval and plot these over the

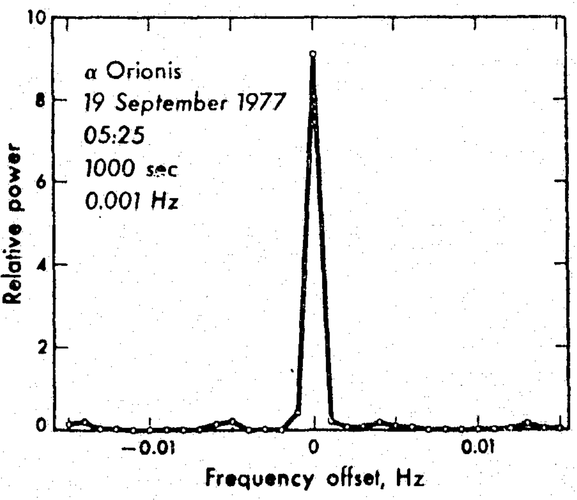

Figure 2: Power spectrum of interference fringe from α Orionis, with 0.0001 Hz resolution

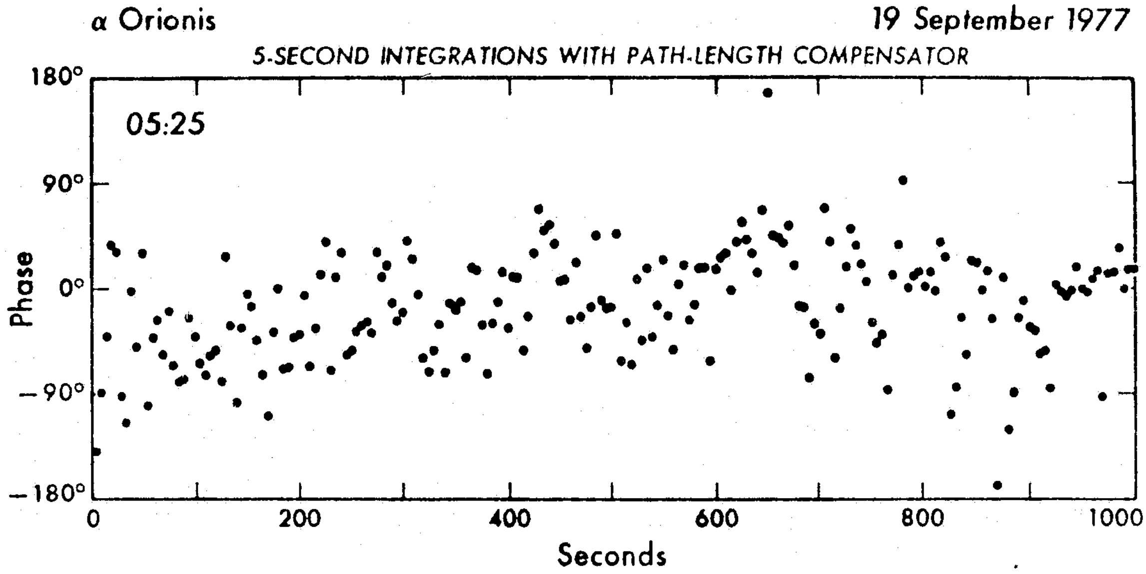

Figure 3: Measured phase of interference signal from α Orionis averaged each 5 seconds.

duration of the integration, we obtain Figure 3. A linear regression has been fitted, as the position of α Orionis is presently known to better accuracy than the orientation of our baseline is. The rms phase uncertainty here is 49°. Since the fringe spacing is 0.43 arcseconds, this corresponds to a positional accuracy of 0.06 arcseconds for a 5 second integration.

While the McMath telescope is well suited to this work in having a stable platform with two independent 30" telescopes, it suffers from the disadvantage that each infrared beam must pass through 120 meters of enclosed region before reaching the detector. This causes seeing fluctuations inherent in the telescope. Fortunately it is possible to correct for a large part of this by monitoring the optical path length within the telescope tunnel. Figure 4 shows the path length compensator. Instead of beating the lasers together on the optical table, each laser beam is made to travel up the tunnel adjacent to the signal beam before being mixed in the beat note detector sitting on top of the tower between the two primary mirrors. The 5 MHz laser beat note then contains the same tunnel-induced phase fluctuations that the interference signal does, and in the course of the signal processing these fluctuations

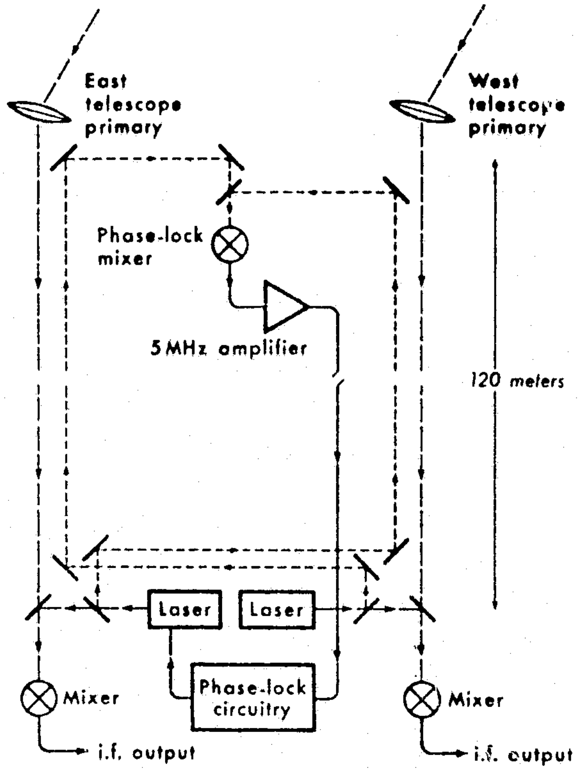

Figure 4: Path Length Compensator

will cancel. In principle the path length compensator will also correct for slow creep in the positions of all but the primary mirrors. Naturally it can do nothing about the atmosphere above the telescope or the rigidity of the primary mirror bearings.

In Figure 5 we see two integrations taken with the path length compensator, and two without. Here the fringe phase in each 100 second interval is plotted as a function of time throughout the integration. The compensated phase plots show a clear improvement; the remaining rms phase uncertainty of the 100 second averages is 15^{o}.

Figure 6 shows the rms phase uncertainty plotted as a function of integration time. This data was obtained from a single integration by averaging for various intervals before fitting a linear baseline and calculating the residuals. Even for a 5 second integration the system noise contribution is very small (adding in quadrature to the seeing noise) and is assumed to decrease with the square root of time. The data show that log phase uncertainty decreases linearly with the logarithm of time, phase error being proportional

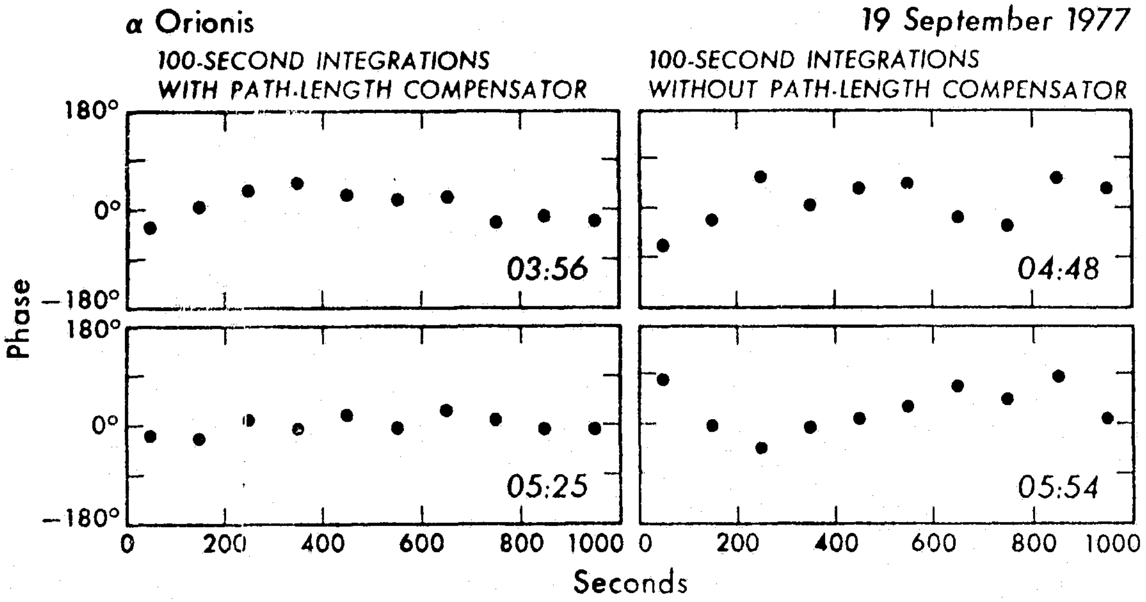

Figure 5: Measured phase of interference signal from α Orionis averaged each 100 seconds.

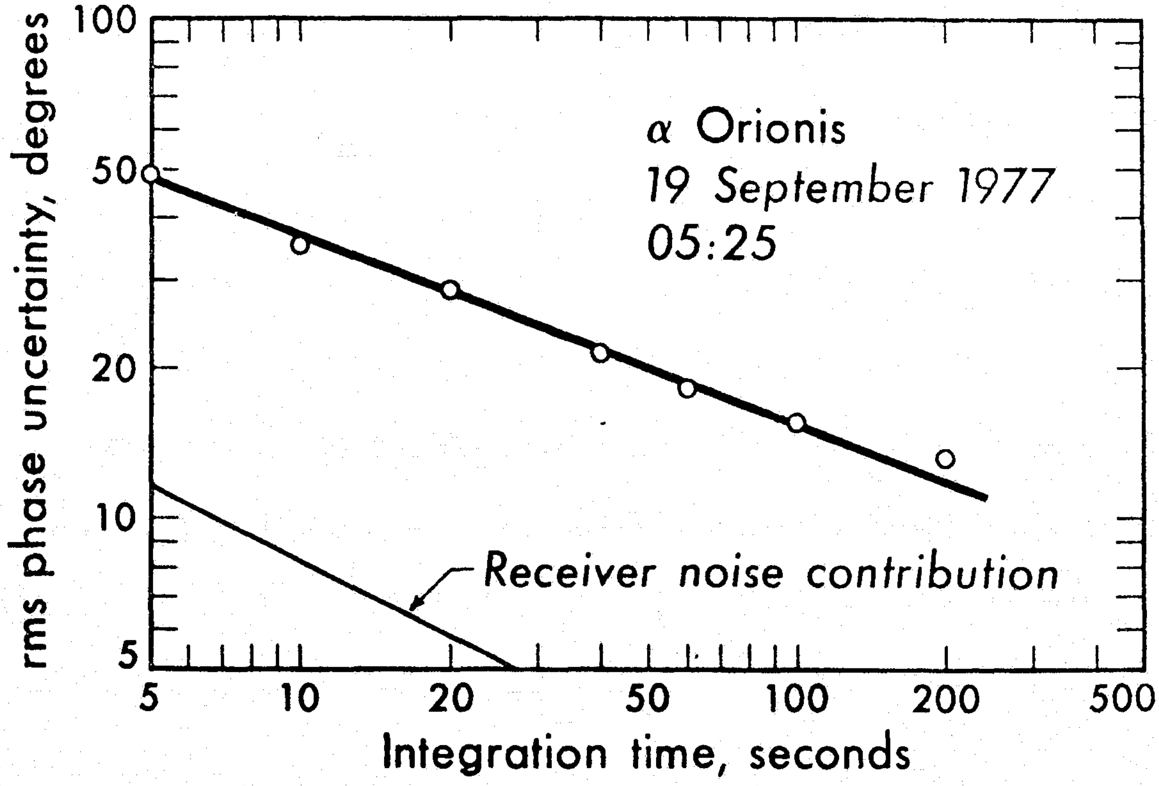

Figure 6: Measured phase uncertainty of the interference signal plotted as a function of integration time.

to time to the -0.37. For 200 second averages the phase uncertainty is 13^{o} rms, implying a positional accuracy of 14 milliarcseconds.

The rate at which the uncertainty in the phase determination decreases with integration time depends on the frequency spectrum of the phase fluctuations. In general it appears that the fringe power at frequencies near 1 Hz falls as $(\nu - \nu_{o})^{-n}$ where ν_{o} is the fringe center frequency and n ranges from 0.6 to 1.3. The most important region for astrometry is the very low frequency components, and it is unfortunate that these are rather difficult to measure directly.

3 FUTURE POSSIBILITIES

The ultimate performance that an infrared interferometer could achieve depends on how the phase coherence changes when we extrapolate the present results to longer baselines, larger and more stable telescopes and longer integration time. The effects of most of these parameters can be analyzed with some certainty from what is already known. Effects on phase measurements of lengthening the baseline are the most difficult to extrapolate since they depend in some detail on the nature of the atmospheric fluctuations over dimensions for which random turbulence theory may not be appropriate. However present measurements which show long term phase stability and sensitivity enough to measure phase in a rather short time give assurance that the present 5.5 meter baseline could profitably be scaled up to a few tens of meters or possibly even 100 meters. The fringe spacing at this baseline would be 20 milliarcseconds, and depending on the signal-to-noise ratio obtained on a particular star, the achievable positional accuracy could be considerably greater than this. Naturally the telescope baseline and the ground upon which it sits must be stable to within the same precision as is desired in the astronomical measurement.

In principle a significant gain in sensitivity could be realized by using direct detection rather than the heterodyne scheme presently in use. In such a scheme the infrared beams are brought to a common focus and interfere before detection, as in Michelson's interferometer. The sensitivity advantage of direct detection lies partly in the much greater infrared bandwidth that can be detected. The penalty that must be paid is one of increased complexity, for now the infrared path lengths must be equalized with some kind of continously variable optical delay line. For measurement of simple stellar sizes via the visibility function, the delay line must be accurate to a small fraction of the coherence length, which of course, is getting shorter as we increase the infrared bandwidth. For astrometry, however, the constraint is much stiffer, for now any variation in path length is equivalent to a tilt in the baseline of the same amount. For a 100 meter baseline and an angular resolution of 1 milliarcsecond this means an accuracy of 0.5 microns. A further advantage of heterodyne detection appears when we consider aperture synthesis with several telescopes, for the i-f signal can be amplified before being split between the correlators, hence avoiding any loss in signal-to-noise ratio.

Finally, it is worthwhile to examine how many objects could potentially be studied. With our present heterodyne system, the NEP is 4×10^{-15} $W/\sqrt{Hz}$, and with 30" telescopes, objects of magnitude -4 can be measured. Forseeable system improvements should yield a sensitivity improvement of about a factor of 2.5. With 60" telescopes and good coherence such a system could measure objects as faint as +1 m in 1 hour. Hall's Catalog of 10 micron Celestial Objects[7] lists 268 stars and 18 non-stellar objects brighter than this, but there is reason to believe there are many times this number of uncataloged objects. If we look at the number of objects in Hall's Catalog brighter than -1, we find 121. Using this figure, and assuming that stars are uniformly distributed through space implies there should be nearly 2000 stars of magnitude brighter than +1. The number of observed visible stars increases somewhat more slowly than this with increasing radius, but direct comparison to the visible situation still implies over 1000 detectable infrared stars.

Another relevant question is how well do these infrared stars relate to the standard visible stars. If we examine the 268 objects listed in Hall's Catalog, we find 76% are also listed in the Smithsonian Astrophysical Observatory Atlas and 21% in the FK4 Catalog[8]. A significant fraction of accessible infrared stars are thus already well established as visible standards, yielding datum points by which a net of infrared astrometry measurements could be related to the visible and radio.

An infrared interferometer is thus an attractive instrument for astrometry as it is able to make measurements of the relative positions of stars with a precision independent of how widely the stars are separated, or the amount of time that elapses between measurements. If, as appears likely, the infrared is less sensitive to meteorological wedges of water vapour, these precise measurements will be particularly useful in studies of time and of local geological behavior. The infrared region also appears attractive simply from an engineering point of view, as neither the sub-micron tolerances of an optical instrument nor the intercontinental baselines of a radio interferometer are necessary in order to achieve milliarcsecond resolution.

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